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A thermal assessment for an innovative passive cooling system designed for flat roofs in tropical climates

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Abstract

This paper presents a thermal performance evaluation of an environment conditioning system so-called Hydrodynamics Cool Roofs System with Energy Recovery. It was created to reduce indoor temperature of flat concrete-made roofs of buildings located in tropical climates. The system can be installed in new and existing buildings.
The building roof is refreshed when the water pass through the system placed on the rooftop; due to the cooling nature of this technology no water is wasted by evaporation and its usage is suitable for hot-humid climate.
This work employed finite element software to carry out CFD simulations to find the theoretical thermal performance of the cooling system. The roof of a control test building and the roof of a study case building were used in the experimental approach where the developed prototypes were tested to determine their cooling potential.
The results shown that the system can diminish in 8 °C the climatic control task for the hottest hours of a habitable space in tropical climate when ambient temperature exceed 35 °C .

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Keywords: Passive cooling; Roof cooling; Climatic control task; Solar radiation; Water heating

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Nomenclature

AC: Air Conditioning; CFD: Computational Fluid Dynamics; CCT: Climatic Control Task; CUICA: University Centre for Research in Environment Sciences; GSR: Global Solar Radiation; PCS: Passive cooling systems; SHETRE: Hydrodynamics Cool Roof System with Energy Recovery; SMN: National Meteorological Service; TO: Thermal Oscillation.

1. Introduction

According to Al-Obaidi et al, the tropical region is an uncomfortable climate zone that receives a large amount of solar radiation, high temperature, and humidity levels as well as long periods of sunny days throughout the year [1].

In 2013 Solar GIS presented a world map of global horizontal irradiation; it shows that the zones receiving more than 7 $kWhm^{-2}$ corresponds to those of lower latitude; the most irradiated zones are South Asia, Africa, and Latin America located between the Tropic of Cancer and Equator [2]. Saikkonen et al stated that the hottest zones present annual mean temperatures between 31 and 35 °C [3]. The Climate Normals for the city of Colima, Mexico obtained by the National Weather Station during 1971 and 2000 presented a month maximum average temperature of 36.2 °C and an extreme daily maximum average temperature of 42 °C [4].

Givoni and Szokolay, observed that in tropical zones the main thermal energy absorbed for a habitable space is due to the heat flux that crosses the roof [5], [6]; Alvarado et al stated that in warmer cities, building made of cement-based materials often exhibit unfavorable thermal characteristics including higher interior temperature [7]. Colima, Mexico along with other Mexican cities, in tropical climates, present flat concrete-made roofing in modern buildings for commerce, offices and housing.

During summer days, it is necessary to use an air conditioning system in order to be comfortable in tropical conditions, but the high emissions involved and the costs of the energy inspire the usage of passive cooling systems. Alvarado et al also stated that an efficient and inexpensive passive cooling system is needed that can be implemented readily using commercially available materials to help reduce energy consumption, environment pollution and cost [7].

Raeissi and Taheri demonstrated that the Sky-therm method of covering roof with water filled plastic bags and using movable insulation could reduce both cooling and heating loads of building in regions with large solar irradiation [8]. Nevertheless the main disadvantage of evaporative cooling and Sky-therm is the need of water, which could be a problem in arid regions or other places where water is not readily available in enough quantities during specific time of the year. Nahar et al estimated that evaporative cooling would need 50 lm-1 of water per day in order to be effective [9]. In humid regions, such passive cooling systems are less effective because of lower potential of evaporation at higher relative humidity levels. Furthermore, the permanent humid conditions of roof ponds bring mosquito and health diseases like Chikungunya virus (CHIKV) which is more real than ever throughout the tropical and subtropical regions of the Americas according to Vega et al [10].

The study of Chavez end up with the design and development of a Hydrodynamic Cool Roof System with Energy Recovery (SHETRE for its acronyms in Spanish), which is a new roof cooling system that has been developed to experimental prototype [11]; the present research aims to determine the thermal performance of the passive cooling system developed by Chavez by studying the indoor temperature of two test buildings in the tropical climate; the present approach employs field experimentation and CFD simulation analysis to obtain a correlation in order to perform further simulations for splitting the hydrodynamic effect from the shading.

1.1. Description of the SHETRE

The SHETRE consists of interconnected modules that cover the roof of a closed habitable space aiming to refresh it; the system is fed by the domestic water supply network. The fundamental of this system is the absorption of the solar radiation by the modules of the system, and the heat transfer to the water particles moving inside them [11]. Fresh water is renewed in the system every time that hot water is consumed for human activities in the building.

According to Geetha's chart of passive cooling methods for energy efficient buildings [12], the studied system herein implements two categories: Solar and heat protection and thermal moderation.

Basically the modules of the system are hollow pieces with the geometry shown in Fig. 1, integrated by the top and the bottom plates creating a bi-convex geometry like an ampulla where the water circulates, it is surrounded by a horizontal square fin aligned with the center to provide solar protection.

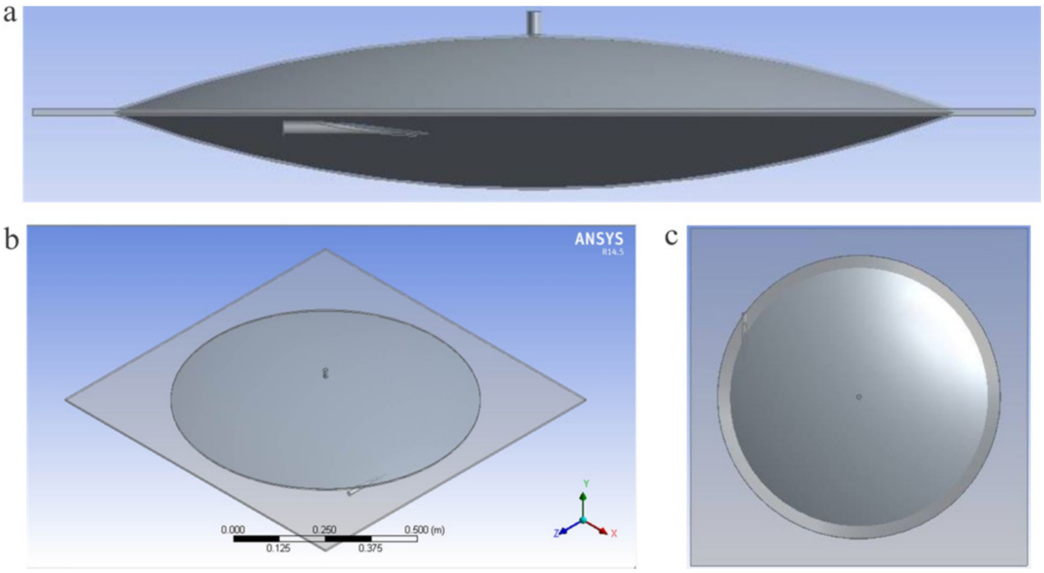

Fig. 1. Design and views of the SHETRE (a) Side (b) Isometric (c) Front

The modules simulated in the analytical approach and the prototypes used in the experiments were made of PMMA sheets 3 mm of thickness, every module covered a roof surface of 0.7 m^2 and contained a volume of water of 0.031 m^3; measured 0.14 m high and weighted 6 Kg while empty. The water inlet had a 0.012 m. diameter pipe placed tangential to the circle shaped by the unification of both plates [11].

The hot water outlet had a 0.012 m. diameter pipe placed vertical on the center-top of the module in order to obtain the highest temperature of the water which is in contact with the plate exposed to the sun radiation.

The basic installation consists of SHETRE modules that are placed together on the roof, fed by the domestic water supply network and the output hot water is connected to the water heater tank with 0.012 m CPVC piping as shown in Fig. 2.

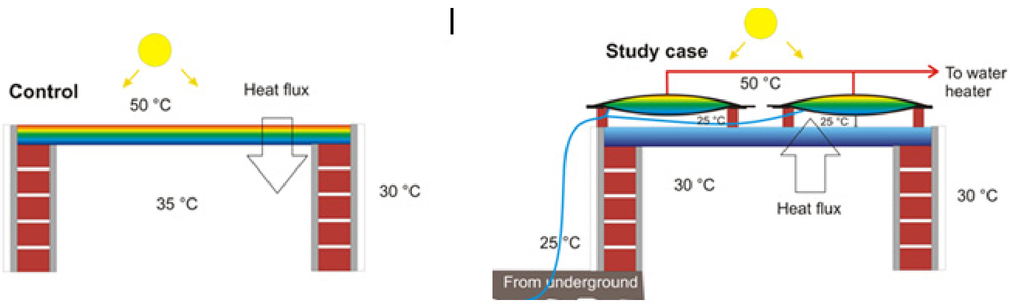

Fig 2. SHETRE installation and operational scheme in the experimental approach.

2. Analytical method

Numerical simulation of the experiment was performed in ANSYS Academic Research Release 12.1 [13] to determine the SHETRE shape and material. To analyze fluid mechanics as well as the heat transfer in the device it was considered an inlet water flow rate of 4.6 x 10^{-3} Kg s^{-1} and inlet water temperature of 25 ºC. The ambient temperatures and solar radiation were obtained from the meteorological center of the Universidad de Colima (CUICA) for a period of six days in Coquimatlan, Colima (at latitude 19º 12' 50.5” N, longitude 103º 48' 12.3” W, and altitude of 364 m). The simulated modules and the prototypes used in the experiments were made of PMMA sheets 3 mm of thickness, every module covers a roof surface of 0.7 m^2 and contains a volume of water of 0.031 m^3; measures 14 cm high and weighted 6 Kg while empty. The water inlet had a 0.012 m. diameter pipe placed tangential to the circle shaped by the unification of both plates [11].

3. Experimental method

Experiment was carried out from October 2012 to January 2013 in humid tropical climate; on two similar test building elements (control and study case) located at the Universidad de Colima, their measurements 1.5 X 1.5 X 1.5 m presented 2.25 m^2 of sky facing surface, corresponding 1.44 m^2 to the roof and 0.81 m^2 to the tops of the walls which were also covered with the system. The test building elements presented a roof thickness of 0.1 m. All envelop walls were made of red brick 0.14 m width with a solar absorption coefficient (SAC) of 0.75 according to Yao et al [14], all the walls were isolated with sheets of 0.05 m thick of expanded polypropylene in the outside surface with a SAC of 0.50 (Fig. 4). U-value for envelope isolated was calculated to 0.07 W m^{-2} K^{-1}. The study case roof employed a SHETRE of 3 modules covering a surface of 2.1 m^2 representing 93.3% of the roof and a piece of expanded polypropylene to ensure total coverage (0.15 m^2); water inlet was set to 4.6 x 10^{-3} Kg s^{-1}. Control roof (behind the study case in Fig. 3) does not have the system prototypes on it; this roof represents the realistic 0.1 m width cement-based roof used for single family housing and commerce in Colima and other tropical Mexican cities.

Fig 3. Experimental approach

Indoor and outdoor temperatures of the air (°C) of both “Control” and “Study Case” test building elements were acquired at only 0.1 m from the center point of each test roof in order to determine the climatic control task, thermal lag, thermal amplitude or thermal oscillation (TO), thermal damping, TO_{indoor}/TO_{amb} ratio and comfort hours of both test building elements. The values of the water temperature at the inlet and the outlet of the system were also registered in order to determine the water heating potential of the system when the water inlet was set to 4.6 x 10^{-3} Kg s^{-1}; lectures were obtained with a frequency of 3600 s using Onset HOBO data loggers U12 with measurement range -20 – 70 °C and accuracy ± 0.35. Values of global solar radiation (GSR) and ambient air temperatures were obtained from CUICA/UCOL weather station. Relative humidity (RH) data were used to find out the indoor comfort hours of both control and study case test buildings using the psychrometric chart of Givoni [15].

3.1. Experimental and analytical methods correspondence

The correlation between analytical and experimental method is found in order to characterize the analytical method and to perform further CFD analysis on sheets of other materials like fiberglass, iron and PMMA aiming to simulate their shading potential to discriminate this effect from the thermal moderation produced by hydrodynamics.

4. Results and discussion

4.1. Thermal performance of the SHETRE by CFD

The numerical simulation was performed using ANSYS *Academic Research Release* 12.1 [13]. The inlet water mass flow rate was set to 4.6 X 10^{-3} Kg s^{-1} and temperature 25 °C. The mesh is shown in Fig. 4 (a), with 18756 nodes and 76165 elements, using the k – epsilon method to solve the fluid dynamics inside the device.

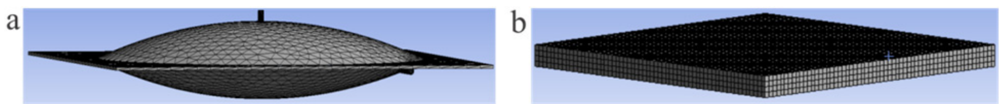

Fig 4. Mesh details (a) SHETRE (b) Roof

To test the numerical method the water outlet temperature is calculated, the results are shown in Fig. 5 as well as the solar irradiation (GSR) and ambient temperatures (WT) used. The average temperature difference is 0.8 ºC. Meanwhile, the maximum temperature difference is 1.7 ºC and represents a 6.7% relative error. According to the general assumptions that we made and the numerical method error a relative error of 10% is accepted.

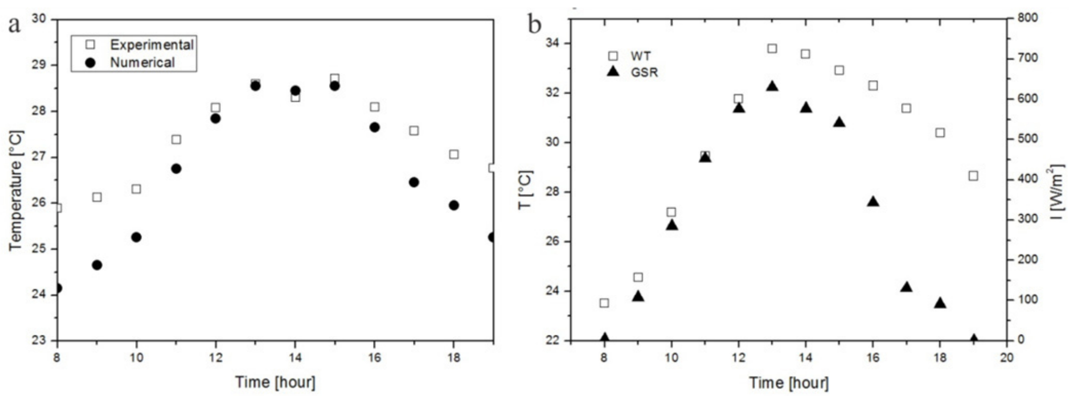

Fig. 5. (a) Solar Irradiation and ambient temperature, 8 December 2012. (b) Numerical and experimental outlet water temperature

Fig. 6 (a). Is a cross section of the water flow inside a module of the system showing the velocity of the flow, it is observed than particles are cycling into the system and those near the center of the device are the slower whereas the particles near the fin go faster; this promote a longer residence time of the water into the system allowing the top plate particles to absorb the heat whereas the lower plate particles remain cool due to the moving action of the new and fresher water particles fed to the system to a mass flow rate of 4.6 x 10^{-3} kg s^{-1}. This thermal effect is shown in

Fig 6 (b) which is the temperature contour of the water into the system where temperatures of 36.7 °C were observed near the top plate whereas temperatures below 28 °C were observed in the lower plate, the configuration of the water inlet and the water outlet play a fundamental role on this effect, however the domestic water supply network conducted underground is necessary to provide with fresh water.

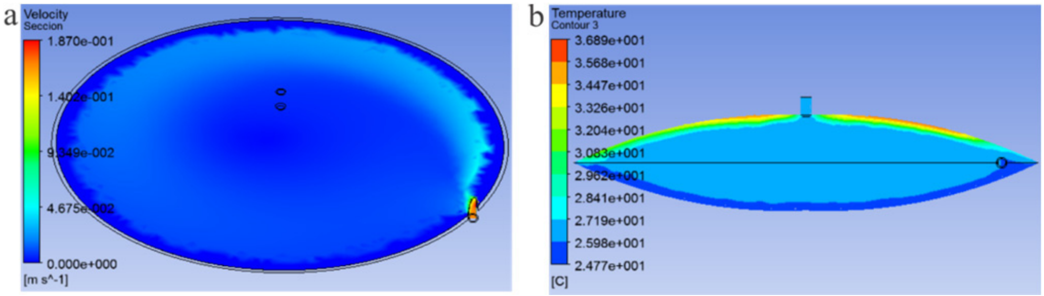

Fig. 6. (a) Velocity of the particles and (b) temperatures inside the SHETRE

4.2. Thermal evaluation of study case roof and the control roof by CFD

The steady state analysis for the 13:00 hrs of December 8th, 2012 reveals that the ambient air temperature of 33.8 °C along with the heat transfer for solar radiation contributed to raise the outdoor surface temperature of the study-case roof to 32.5 °C, whereas the temperature of the indoor surface was only 26 °C. The control building roof presented outside surface temperature of 38.2 °C and the indoor surface reached 30.6 °C; this value is 4.6 °C higher than the indoor surface temperature of the study case roof, the exterior surface of both roofs presents a temperature difference of 5.7 °C.

4.3. Experimental thermal oscillation (TO), thermal damping, thermal lag and TOindoor/TOamb ratio.

Fig. 7 shows the average temperatures collected from December 8th to 23th 2012 corrected by the scale factor, in the experiment, a SHETRE of 3 modules was used above the study case test building covering 2.1 m^2, the rest of the roof surface (0.15 m^2) was covered with 0.025 m expanded polyethylene sheet to ensure total coverage of the roof.

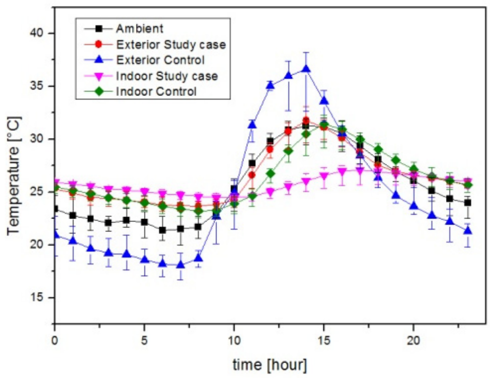

Fig 7. Thermal performance of the SHETRE using 3 modules

In the Fig. 7 a reduction of the indoor temperature of the study case test building is observed from 11:00 AM to 11:00 PM, a maximum difference in the temperature of 5 °C is detected around 3:00 PM when is compared the indoor temperatures of control test building and study case. The indoor thermal oscillation for control test building was 8.9 °C and for the study case tests building only 3.1 °C. The thermal damping was observed of the order of -0.4

for control test building and 4.1 for study case test building; the ratio of indoor amplitude/ambient air amplitude was 0.80 and 0.28 for the control and study case test buildings respectively.

The thermal lag of control test building was of 1 hour, whereas the study case test building was found of 2.5 hrs.

The roof outside for control test building presented an thermal oscillation of 20.1 °C and the study case only 8.7 °C, a reduction of 11.4 °C in the roof outside thermal amplitude for the employment of the passive cooling system.

4.4. Analysis of psychrometric charts of indoor temperatures for the study case and control test buildings.

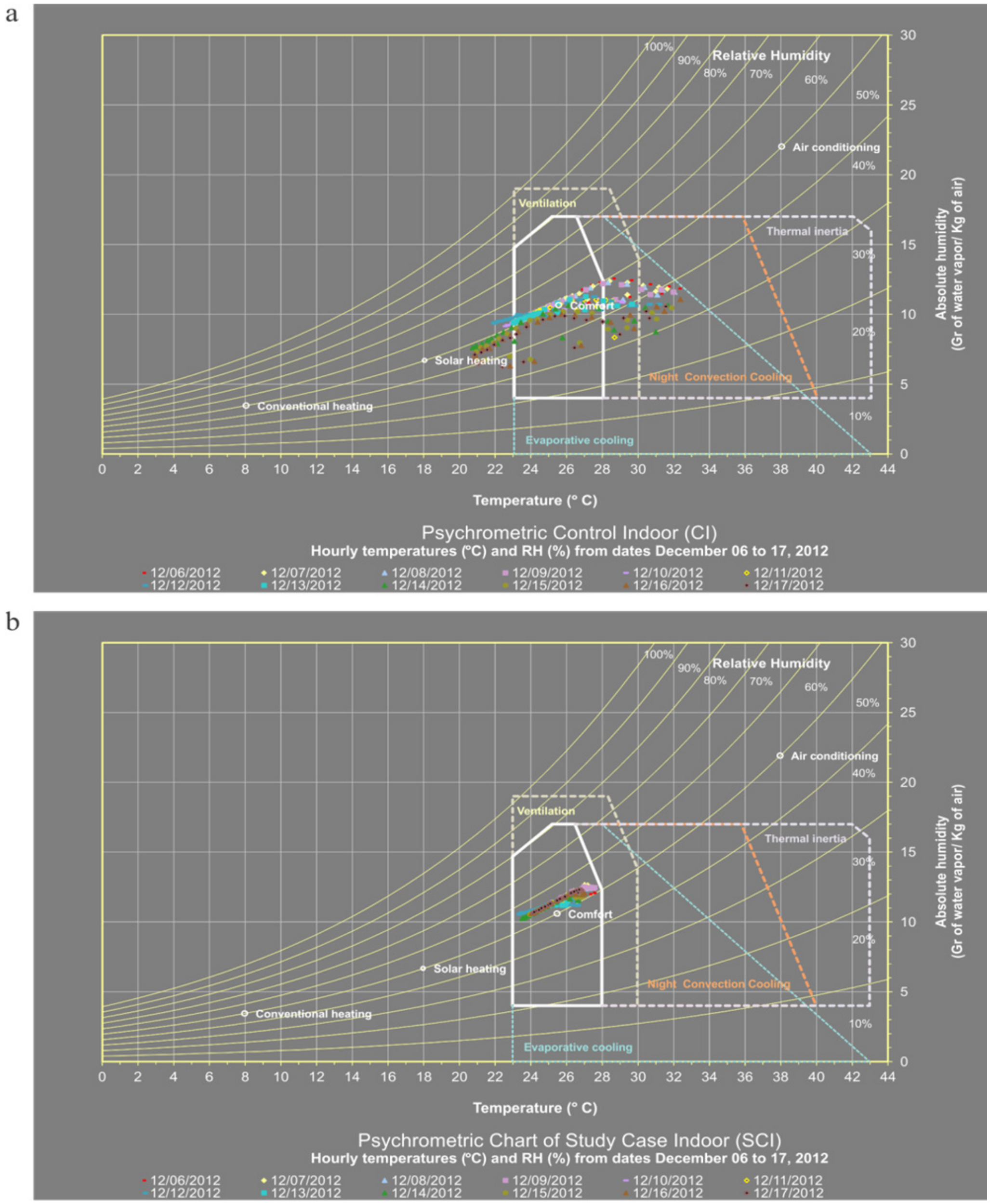

Fig. 8. Psychometric charts for (a) control building and (b) study case building at the end of autumn

Fig. 8, shows the hourly data for the temperature and relative humidity from a period of 12 days from December 6th to 17th , 2012 recorded 288 points expressed in the psychometric charts [15] for control (a) and study case (b) test buildings. The psychrometric chart was designed for the specific climatic conditions of Coquimatlan Colima and for that particular period of time using the approach of De Dear, Brager and Gail [16] that evaluates the temperature of comfort as a function of the mean ambient temperature obtained with the expression 1; hence the comfort zone band extends ± 2.5 °K from this value of T_{comf}.

$$T_{comf} = mT_{amb} + b \tag{1}$$

Where: T_{comf} is the optimum comfort temperature, Tamb is the mean ambient temperature (24.8 °C obtained from UCOL-CUICA), *b* and *m* are values from the approach of [16] for the construction of thermal comfort models (17.8 and 0.31 respectively)

A T_{comf} of 25.5 °C was found for the period of autumn in Coquimatlan, using the approach of [16] the mean comfort zone band of 5 °C extends from 23 to 28 °C. Records of temperature and relative humidity from 5 periods of 12 days each (1440 hourly values from mid-autumn to mid-winter), shown 602 hours in comfort for the control test building and 1012 for the study case test building (table 1).

Table 1. Hours in comfort and discomfort of the building elements

Location	Coquimatlán, Colima, México 19º 12' 50.5” N, 103º 48' 12.3” W, 364 masl			
Period	Hours in confort	Hours the building needs heating	Hours the building needs cooling	Total hours
Building Element: Control				
Oct 4-15, 2012	109	0	179	288
Oct 16-27, 2012	114	0	174	288
Dec 06-17, 2012	169	49	70	288
Dec 18-29, 2012	112	111	65	288
Dec 30-Jan 10, '13	98	161	29	288
Total Control	602	321	517	1440
Building Element: Study Case				
Oct 4-15, 2012	100	0	188	288
Oct 16-27, 2012	105	0	183	288
Dec 06-17, 2012	288	0	0	288
Dec 18-29, 2012	277	11	0	288
Dec 30-Jan 10, '13	242	46	0	288
Total Study Case	1012	57	371	1440

4.5. Correspondence between analytical and experimental methods

In order to systematize the analytical method, the linear correspondence approach using indoor temperatures of both buildings found a determination coefficient (R^2) of 0.95 which represents a good correlation between analytical and experimental method according to Ansys, Inc. [13]. A correlation between the experimental and simulated data of R^2 = 0.92 was encountered for water outlet temperature data.

4.6. Further mass and energy simulations employing the validated numerical method

Further CFD simulations were made on December 26th, 2012 in order to discriminate the shading effect of SHETRE from its hydrodynamics effect. The system achieved an additional reduction of temperature of 3.17 °C when it was compared to the temperature obtained with a sole shading sheet of PMMA 3 mm width. Table 2 shows the temperature of both inner and outer roof surfaces of five shadings scenarios including the SHETRE without water to obtain the difference in temperature between each of the inner surfaces of the roofs protected with shadings and the inside surface of the bare roof without shading.

Table 2 CFD simulated temperatures of shaded roof surfaces.

Shading type	**Outer roof surface (°C)**	**Inner roof surface (°C)**	**Outer difference**	**Inner diference**
Without shading	36.98	29.72	0	0
Fiberglass 3mm	34.81	28.11	2.17	1.61
PMMA 3mm	35.10	28.50	1.88	1.22
Iron 3 mm	35.54	28.91	1.44	0.81
SHETRE empty	34.19	28.01	2.79	1.71
SHETRE	28.92	25.33	8.06	4.39

4.7. Water heating potential of the SHETRE in tropical climate

Energy Demand for Domestic Hot Water or EDDHW is defined as the amount of thermal energy necessary to heat, to a specific temperature, a required volume of hot water to take a shower. EDDHW varies with differences of time, latitude, longitude and altitude.

The total amount of EDDHW preparation (Q_{DHW}) is given by expression 2:

$$Q_{DHW} = V_{DHW} \rho C_P \left(T_{DHW} - T_{CW}\right) \tag{2}$$

Where V_{DHW} is the water volume, ρ is the specific weight of water, C_P is the specific heat capacity, T_{DHW} is the desired temperature of water to take a bath and T_{CW} is the tap water temperature as it comes from the water supply network.

A Q_{DHW} of 1354.32 kJ was found to be necessary to rise the temperature of 27 liters of water from 25 to 37 °C in the mean ambient air temperature of Coquimatlan Colima. The system SHETRE is able to recover 829.31 kJ m^{-2} in a clear day in this location [11] therefore 1.63 m^2 of the system covering the roof would be enough to cover personal needs for EDDHW and by covering 7 m^2 of the roof (a bedroom for example), the system should ensure enough hot water for a family of 4 in a clear day. The roof area to be covered should belong to a closed habitable space in order to reduce its indoor temperature.

5. Conclusions

The SHETRE cools the building during the hottest hours, decreasing the indoor temperature in 8 °C in the study case test building compared to the control test building (bare roof) when ambient air temperature reached 35 °C. The hours in comfort were incremented by 68.1 % in the study case test building compared to the control roof.

The water leaving the system increased its temperature by 7 °C when a SHETRE of only three modules covered 2.25 m^2 of the roof, at the end of autumn season on a test building; more meaningful differences of up to 17 °C in the outlet water temperature was obtained by the numerical model employing 10 modules of the system to cover 7.5 m^2 of roof and using the same water flow (4.6 x 10^{-3} Kg s^{-1}), than in the experiment and in previous simulations.

The analysis of the psychrometric chart for 864 hourly values of indoor temperatures for both control and study case elements for the period analyzed from Dec. 6th, 2012 to Jan 8th, 2013 registered 379 and 807 hours in comfort respectively, which means an increment of 213% in the achievement for comfort hours when the system is used.

It is highly recommended to perform new analysis employing the SHETRE in the whole roof of a house or an office to obtain data from real buildings.

Acknowledgments

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